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Civilian Power from Space in the Early 21st Century

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CIVILIAN POWER FROM SPACE IN THE EARLY 21ST CENTURY^

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SUMMARY

If power beamed from space is to be become widely used on Earth in the first half of the 21st century, several thus-far-persistent impediments must be obviated, including threshold effects and problematic aspects of cost, availability, reliability, hazards and environmental impacts. We sketch a generally-applicable route to doing so, noting key enabling technologies and practical features. Likely-essential features of any successful strategy include vigorous, systematic leveraging of all intrinsic features of space-derived power, e.g., addressing marginal, high-value-added markets for electric power in space- and time-agile manners to conveniently provide power-upon-demand, and incrementally 'wedging' into ever-larger markets with ever more cost-efficient generations and scales of technology. We suggest that no prudent strategic plan will rely upon large-scale, long-term public subsidies – fiscal, regulatory, etc. – with their attendant 'sovereign risks' and interminable delays, and that plan-essential governmental support likely will be limited to early feasibility demonstrations, provision of threshold technologies and a rational, competition-neutral licensing environment. If salient realities are uniformly respected and accessible technologies are intelligently leveraged, electricity derived from space-sourced power-beams may come into significant civilian use during the latter part of the first quarter of this century, and may become widely used by the half-century point.

The technologies most crucial for initial civil-electricity market-penetration may be 'GFE,' developed by the U.S. Government for other purposes, e.g., high-precision, high-agility, trans-space power-beaming to satellites, 'space tugs,' etc. Among these enabling technologies are high power-to-mass solar photovoltaic arrays of megawatt-to-gigawatt scales, efficient distributed (e.g., fiber-optic-based) coherent radiation-generating systems operating in the (near-)optical spectrum, and large beam-projection (near-)optical systems, likely supplemented with associated means for rapid beam-pointing-&-steering, -fractionation and -redirection. These may be readily – indeed, quite immediately – leveraged to form and direct comparatively high-brightness beams to their 'highest-&-best' use on the Earth's surface, i.e., to illuminate *ad hoc* PVAs whose operators are currently real-time (auto-)bidding successfully for electric power to be sourced by their space beam-illuminated PVA systems, often calling for illumination intensities which are substantial multiples of peak solar intensity. Space-sourced electric power may thereby be sold to a large population of continuously-selected customers (e.g., in locations remote from electric utility lines and even to moving 'locations') for dollars/kWh, rather than the pennies/kWh often assumed to be necessary for sales to large electric utilities. Indeed, initially servicing many fragmented, widely spacetime-distributed marginal (e.g., 'peaking') markets for electrical power, not a baseload-class one in at most a few spacetime loci, likely is a *sine qua non* for successful early market penetration of any space-based power system. Such a fundamentally novel strategy certainly leverages significantly several of the innate advantages of space-based power-beaming systems.

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Three technical advances are key to realizing this penetration-and-growth market development strategy. The first is a shift to optical power transmission instead of microwave. This step allows shrinkage of the transmitter-receiver area-product by a factor of $\sim 10^{10}$, enabling small electricity users to be serviced from small satellites instead of huge users via huge satellites. This basic technology shift is crucial in allowing this new power-beaming infrastructure to start small and grow-by-bootstrapping rather than being created full-grown from the forehead of some governmental Zeus. The second key advance is the use of very high power-to-mass solar PVAs to generate the required electric power in space from incident sunlight. These arrays can generate electrical power at near-term levels of ≥10 W/gm, with growth potential to >100 W/gm. This technology-gain drastically increases the specific power (kWe/kg) of solar power satellites, and hence increases their economic (We/$) viability relative to space transportation costs. Coupled with the huge reduction in both satellite and user size-scales enabled by optical power transmission, the buy-in investment required to birth this new energy infrastructure can be reduced by many thousand-fold. The final technological advance making this capability not just possible but compelling is the recent advent of advanced coherent radiation generation and beam-forming and projection technologies; these are what make the use of optical power transmission from space generation sites to Earth use-points not merely technically feasible but economically attractive. Related technological advances providing major leverage include the Global Digital Network and its satellite telephony adjunct and the Global Positioning System-derived universal availability of high-precision geolocation (and orientation).

Large-scale market penetration then is likely to follow the Internet model: technologies, scales and unit economies vastly surpassing the dreams of early USG developers and users, perhaps even on single-decade time-scales. Net, it appears feasible *in the present decade* to source electric power anywhere on the Earth's surface at any time for marginal TUEC (total unit energy cost, including capital and operating expenses) of less than $1/kWh and a corresponding capital cost of the order of $10/W, easily sufficiently economical to support swift penetration of the (highly-fragmented and widely spacetime-distributed) highest-added-value markets for on-demand electrical power, especially when transmission and distribution savings are included. The >100-fold gains already seen to be technically accessible then can be developed and leveraged to penetrate ever larger and less marginal markets, eventually accessing even large baseload ones, e.g., the huge automotive market will open up at delivered-energy TUEC of ~$0.3-0.5/kW(e) in the U.S. and about twice that TUEC in Europe.

The route to space-sourced, large-scale electric power supply on the Earth's surface thus is seen to proceed via beam-projection at optical, rather than microwave, frequencies; to serve many 'early' customers, rather than a few; to involve 'early' customers having 1-1000 kWe requirements, rather than those presenting ≥1 GWe loads; to power typically quite intermittent, rather than usually steady-state, customers; to be conducted via second-to-second auto-executed energy/power sales contracts, rather than year-to-year 'manually'-negotiated, ones; to be commenced with MWe-scale facilities-in-space that are funded privately, rather than GWe ones financed from public treasuries; and to strongly leverage other modern technologies such as the Global Digital Network and the Global Positioning System (GPS) to enable 'small-granularity' transactions with very small transactional 'frictions' and with great spatial and temporal (and even orientation) precisions enabling the servicing of even highly-mobile customers.

Market penetration of space-sourced electric power for the full spectrum of Earth-based uses is predicted to be soon, incremental, steady and based on advantage-seeking by individuals and private entities, rather than in-the-large (including elapsed-time-until-first-use) as a consequence of government policies, statutory decrees and bureaucratic expenditures.

Introduction. Peter Glaser joined the company of the Great Visionaries of humankind a quarter-century ago when he proposed large-scale power-beaming from space for Earthside baseload electricity generation. This was the first specific proposal toward humanity's realization of a Dyson Sphere about its own star, and thus must be regarded as a signal landmark in the technological history of our kind.

However, a quarter-century hence – during which time more overall technological advance undeniably has taken place than in all previous human history -- there is as yet no discernible, "bootprints in the sands"-quality progress that has been made in this direction. Most peculiarly, in the meantime, great concerns have been raised regarding each-&-every type of extant Earth-based means of power generation. How is this "great contradiction of our times" to be understood, and what's to be done about it? These issues are the subject-matter of this paper.

Why Space-Sourced Beamed Power? Space-sourcing power for the full spectrum of human activities is so obviously advantageous that it's *deeply* surprising that it's not already being done in this, Year 47 of the Space Age. To be sure, radiant power beamed from a nearby star – indeed, from the nearby star – has powered most things terrestrial (volcanoes, earthquakes, hydrogen bombs and nuclear power reactors being notable exceptions) from The Beginning. However, this flavor of space-sourced power-beaming is free, natural – and unavoidable – and so, in the finest modern physics tradition, we unapologetically subtract this (near-)infinitude from present considerations, and solemnly proceed with the matters of present interest. In acute contrast, in the 47th year of the Air Age, humankind – far poorer economically and much more impoverished technologically -- had advanced technically from powered gliders that could barely transport a single person a couple of hundred meters to bombers that could carry city-busting bombs half-way around the planet. In further contrast, in Year 47 of the Radar Age, signals were being employed routine to map the mesoscale surface features of planets hundreds of millions of kilometers distant, moreover in the face of fourth-power-of-the-distance propagation losses, and the associated antennae also were being used to receive watt-level spacecraft telemetry signals beamed across an entire stellar system (that of Sol). Finally, in Year 47 of the electronic digital computer age, such devices already had become huge foundation-stones of modern civilization, ubiquitous in human affairs. How, then, after nearly a half-century of spacefaring – and, at least as importantly, why – have we fallen so short in space endeavors generally and most particularly in the purposeful utilization of space-based means for addressing our energy-supply needs, and what's to be done about it?

Prime Mover Problems: Fuels, Ashes, Entropy, Etc. It's not that the main prime movers powering human civilizations are ideal in all respects – or even in any major one. Supplying hydrocarbon fuels to them not only distorts much of contemporary international affairs – to the extent of underlying at least two major conflicts in the past dozen years and several other less intense but far more bloody mass homicides over the same interval – but likely will do so at an ever-accelerating pace over the next few decades, as these fuels become ever more scarce and thus more valuable (at least in the surprise-free scenario). Sourcing fuels to nuclear power plants isn't so pervasively problematic, but such fuels seem to be in remarkably short supply relative to presently employed means – light-water reactors (LWRs) -- of generating nuclear power in usefully large scales, and alternate means haven't surfaced meaningfully despite a half-century of various efforts. Supply of 'renewable' energy sources in usefully-large quantities to the principal engines of civilization has proven to be persistently expensive, in spite of decades of governmental nurse-maiding of them, and the present-day outlook for their becoming truly economically competitive on usefully-large scales isn't confidence-inspiring to reasonable skeptics.

The consequences of powering large-scale prime movers of the present energy era are even less happy. Oxidation of hydrocarbons produces oxides – surprise! – not only of carbon and hydrogen, but even of the nitrogen component of the air typically used to supply everyone's favorite electron-acceptor, molecular oxygen. Now thereby creating hydrogen oxide – water -- is still politically correct, but the resulting carbon and nitrogen oxides, though dearly-beloved by all plants, are viewed with ever-increasing alarm by those resolutely committed to at least the atmospheric aspects of the *status quo ante* of contemporary human civilization. Moreover, imperfect oxidation of hydrocarbon fuels – e.g., generation of carbon monoxide – is disfavored generally (albeit not for efficiency reasons), and oxidation of minor and trace components of hydrocarbon fuels – e.g., sulfur and heavier metals – is quite widely viewed with dismay, if not outright alarm. Quite recently, intensive-but-imperfect oxidation of hydrocarbon fuels has been blamed in the technical literature for mesoscale climatic anomalies – multi-year droughts and floodings -- in China and in India, via largely independent atmospheric mechanisms, and oxides of sulfur and heavier metals have been blamed by experts for widespread albeit mostly subclinical respiratory illness in urbanized China; ground-level ozone resulting from hydrocarbon power production has been authoritatively blamed for aggregate crop-losses amounting to 10% of total cereal-grain production in China, or about 200 calories/day per capita of human food-equivalent. Finally, it's become enormously fashionable during the past decade to forecast amazing changes in large-scale climate a century hence, due to an increase of the order of 1% in atmospheric radiative forcing arising from continually-increasing inputs of carbon dioxide and methane – the latter being a presently-favored hydrocarbon fuel which inevitably leaks to some extent into the air – into the atmosphere, and many such forecasters have chosen to dwell on the downsides of such anticipated changes, so that the 'ashes' from hydrocarbon-based energy production have come to be regarded – at least in the more politically correct circles -- as shadowing humanity's long-term future.

The 'ashes' from nuclear fission energy generation aren't regarded much more warmly by many involved in the energy forecasting business, in spite of their million-fold smaller mass per unit of energy generated. While one possible interpretation of this might be that these folks just don't care for large-scale energy production of any nature, the more conventional view is to the effect that even relatively very small masses of nuclear fission 'ash' may be quite problematic. To be sure, ocean disposal of all of the nuclear power-plant waste that human activities could possibly produce during the entire 21st century wouldn't increase the total radioactivity of the ocean by even 1%, and moreover this increase would die away in a few decades' time; however, quantitative considerations generally aren't warmly received in these discussions, which instead tend to focus on favored nightmare scenarios involving the undeniably-substantial mass-flows of fissile isotopes internal to various nuclear fuel cycles, and the possible use of even tiny fractions of such flows in nuclear fission explosives. The bottom line is that nuclear fission energy generation doesn't enjoy even as good public reputation regarding its side-effects as does that based on oxidation of hydrocarbons, in spite of the objectively far smaller loss-of-life from the former vs. the latter per unit of useful energy produced – proving once again that humanity does indeed stick with the devil that it knows. Nuclear fusion-based civilian energy-production, if-&-when it ever occurs on large-scale, is authoritatively predicted to be greeted with comparable levels of dismay regarding its radioactive and weapons-related 'by-products,' though the technical details of such discussion will apparently be very different from the present ones centered on nuclear fission power.

Renewable energy sources are renowned for generally not have ashes-of-significance, but the consequences of extracting energy from wind, water, sunlight -- or chicken manure -- somehow come to be regarded as unacceptably severe whenever one or another of these sources even bids to attain to significant scale. Bird losses from operation of wind farms – to say nothing of currently-contemplated scenery-desecration by sea-based windmills proposed to be located off of Cape Cod – apparently can't be tolerated, nor can hydroelectric dams and their asserted depression of wild fish runs and/or canyon sedimentation fine-structures be tolerated, nor can land-use losses from large-scale solar photovoltaic 'farms' be accepted. In short, using land, scenery or even 'free air' for large-scale energy generation involving 'harvesting' of energy recently sourced into the fluid envelopes of the Earth by the Sun seems to not be qualitatively less problematic than does liberating energy long-ago sent to Earth from the Sun – or even that deposited on the Earth during the Solar system's birth in the form of long-lived isotopes of the actinide elements.

As if these problematic supply and ash-disposal issue-sets weren't sufficient by way of show-stoppers for large-scale energy production, increasing concern is expressed regarding the low-temperature waste heat invariably generated as energy is produced in support of human activities. 'Urban heat islands' are viewed with increasing alarm as generators of microclimatic shifts, and the loss in the form of 'waste heat' of 2-4 times the energy put to use – in conventional Rankine-cycle electric power-plants and in typical automotive engines, respectively -- is increasingly decried as unacceptable. 'Entropy pollution' seems likely to enter the jargon of those opposed to large-scale energy production/utilization, to the extent that it hasn't done so already. In short, humanity – or at least the current preponderance of the chattering classes and the politicians who are specially receptive to the wisdom they dispense -- seems ready in several independent respects for qualitative improvements in the human race's large-scale energy supply system.

Space-Origined Beamed-Power As The 'Electric Ideal.' Electric power – and, derived readily from it, all other desired forms of energy – that leaps exactly when bidden, like a genie from a lamp, from a low mass, volume and cost container to serve human needs, seemingly is the ideal for energy supply on all scales. Realizing a petit, inexpensive, side-effects-free "black box" that sources any desired quantity of electricity-on-demand seemingly would be a great advance. Power generated in space and beamed to points on/about the Earth's surface, there to be converted by cheap, compact equipment into the desired electrical forms with no material by-products and at high efficiency, seemingly would do just this. Why, then, isn't it being done – or, indeed, why isn't it already in widespread use?

Why *Not* Space-Sourced Beamed Power? Consider just what stands between us and large-scale use of power sent to use-points from space sources thereof.

Buy-In Costs. First of all, of course, there are the 'buy-in' costs, those associated with preparing to do something for the first time. We have neither power stations in space, nor equipment or facilities on the ground for receiving power beamed from them, nor means for getting power so generated at ground-points to use-points. Furthermore, it's not clear what fraction of the basic technologies – the building-blocks from which such systems could be assembled – even exist, or how hard it will be to perform such integrations for the first time. Non-existent technologies may have costs-to-realize that are difficult to estimate reliably. Such overall space power system cost estimates as do exist generally have been generated in what might most delicately be characterized as "cost-unfamiliar circumstances" – i.e., government-sponsored studies performed largely or totally by either *de facto* or *de jure* academics – and are often criticized as being either out-of-this-world optimistic or so programmatically grand and all-inclusive as to be intrinsically quite decoupled from real-world economics. At that, they almost invariably involve expenditures of tens of billions of dollars prior to attainment of positive cash-flow from power sales in real markets. Capital markets just don't support such first-time, up-front costs – ever, anywhere, for any purpose. Market capital flows to highest-&-best uses, i.e., to where risk-discounted returns are the greatest. Risk premiums on doing very large-scale things for the first time are generally of prohibitive magnitudes, as the English Channel Tunnel and IRIDIUM satellite telephony experiences recently exemplified. Even today, only very rich governments throw ten billion dollar chunks of capital at a "good idea" with no real thought for getting it back with market interest – and they don't do this very often at all. Thus, merely "getting off the ground" with space-based power is a real challenge – if ~10^{10} up-front capitalization is required.

Continuing Costs. We live in a world in which the most modern, pollution-controlled, coal-fired electric power plants deliver electrical energy to the transmission system in the American Midwest at a total unit energy cost (TUEC) of $10/MWh -- $0.01/kWh – while modular dual-cycle natural gas-fired units currently produce it in American urban-industrial load-centers for a TUEC of ~$0.05/kWh (nearly 75% of which is fuel cost). While such real-world sales prices might be claimed to involve all sorts of hidden subsidies, unfunded externalities, etc., etc., all such claims are termed "whining" in the world of power politics, and are seen as tantamount to a demand for preferences, overt subsidies, and so forth for some alternative electricity source. It is this world into which space-derived power must be sold, and the price-competition is daunting to contemplate. Four megajoules of electrical energy put onto the transmission grid for a penny, or an electrical megajoule delivered directly to an urban load under acceptable environmental conditions for the same penny is a *very* fine deal – and it's undeniable that space-based power will find it most challenging to offer comparable terms, even when it's highly mature. How it could ever *commence* to sell into such marketplaces -- when its technologies will be least mature, its scales will be smallest and thus its TUECs highest -- isn't at all clear.

'Accidents-&-Incidents'. It's undeniable that we humans have very strong preferences for the devils that we know; we're far more risk-adverse when the risks are unfamiliar, for the same overall risk-level. Currently, we lose ~100 of our fellow Americans to automobile-based fatalities every day and think about this very little, but we still go into prolonged national fits of introspection and fault-finding over an astronaut loss-rate averaging less than 1 per year; after a century of bearing losses of this type, the former type of tragedy is a commonplace, while the latter one is still quite novel and thus terrible. So it will be with any novel form of power generation, as the history of nuclear fission power makes abundantly clear: mountains of uncontroverted statistical evidence establish that the life-lost per kWh of nuclear electricity is a few percent of that lost due to coal-derived electricity generation, but nuclear electric power development has stalled out worldwide in favor of more intensive development of coal-derived electricity, largely on the basis of perceived risks.

Space-based electrical power will be no different; power beams from space will be accused of everything noxious from causing cataracts on bird-eyes to inducing cancer and birth-defects in those humans conceivably exposed to the fringes of the descending beams. Beam-steering accidents – and they will occur, although their frequency and severity may be very low – will be featured luridly in song-&-story by opponents, which assuredly will exist even for such benign energy supplies. Thus, the political costs of such accidents won't be negligible – and may not even be all that small. Whether such costs can be sustained must be considered to be an open question, likely for decades to come.

Beam Obstacles, Bad Weather And Contingencies. Depending on physical characteristics of the space-originated power-beams, they will be subject to attenuation – and possibly effectively-complete obscuration – by obstacles both natural and man-made. Obvious example include optical-frequency beams in heavily-clouded circumstances, or failure of any type of beamed power-delivery to tall building-occluded receivers. Depending on the quality of work-arounds, these may range in significance from minor annoyances in unusual circumstances to frequently-encountered, serious-quality impediments. If space-derived power is to become regarded as quality-comparable to electricity from the wire mains of electrical utilities, it must comparably reliable and at least as ubiquitous; space power-beams of various types may find one or another of these qualities difficult to attain, necessitating back-ups having significant costs (economic or otherwise). Finally, all-causes outages of space-originated power must be graceful, i.e., no more frequent in the time-average than the ~10 hours/year of utility power outage which is the *de facto* U.S. standard.

'Last Mover' Disadvantages And Intellectual Inertia. It's fashionable in high-tech circles to speak of 'first mover' advantages, the (widely perceived, if not altogether real) edge enjoyed by the first entity to commence servicing a new market. Electricity has been around on large-scales for about a century now, and there's lots of folks who supply it in various forms, locales, scales, price-ranges, etc. They know their markets, they have their customers, they understand their regulators, they support the successful politicians who govern their marketplaces -- and they're more-or-less firmly resolved to stay in business, and perhaps even plan to expand their market-share. They'll probably not willingly surrender market-share to newcomers, and they'll use all means – economic and non-economic – at their disposal to avoid doing so.

In their efforts to retain market-share, they'll enjoy the fundamental advantage that humans are not only risk-adverse and moreover are exceptionally adverse to novel risks, but also are change-wary, even when stay-or-switch risk-differentials are perceived to be small. Thus, if space-originated beamed power is to succeed in the real world, it must be *significantly* advantaged over the incumbents in the markets which it attempts to penetrate, if such penetration is succeed at all, let alone in an economically-timely manner (recalling that "Time is money").

It's likely worth considerable intellectual effort to understand just why space power can rationally be *expected* to succeed in accessing markets of interesting scales, all of the foregoing considered. When doing so, it's necessary to recall that contemporary energy ventures with significant risk – e.g., opening up new oil fields – are required to have credible business plans showing returns-on-investment (ROI) of the order of 30%, or investment payback times of 30-36 months. Since it seems likely that any non-governmental capitalization of space-based power plants will be competitively accessing the same type of capital pools, it's only realistic to plan realistically on attaining comparable ROIs. Much later, when space power technology is far more mature and its workability no longer doubted by anyone, it may be feasible to capitalize new space-based power-plant capacity on the basis of 20-40 year service lifetimes, with comparably leisurely amortization schedules; however, the past two centuries of history of new types of utilities – rail transportation, electricity, gas, telephony, etc. – quite uniformly informs the student that few-year-duration paybacks are demanded almost invariably by private investors in novel utility enterprises.

Key Technical Ways-&-Means. We now consider a set of specific technical approaches to space power plants that we believe, if innovatively employed, can satisfy the rather stringent set of 'practical' requirements just sketched.

Primary Energy Sources. From a purely technical-economic standpoint, it's not entirely clear what are the most preferred prime movers – the primary energy sources – for space-based power plants. Nuclear fission reactors, in principle, have the two great advantages of arbitrarily high power density (e.g., >>100 W/gm specific thermal power) and very high temperature (>=1500 K) long-term operation, so that they can at once be very compact (i.e., of comparatively very small mass and volume, in the context of facilitating space launch) and operate with high-temperature (and thus area- and mass-efficient) waste-heat-rejecting radiators. Thus, we consider the type of automatically self-regulated thorium- and natural uranium-burning power reactors that we discussed several years ago* for long-term untended operation deep underground to be outstanding candidates for the prime mover function in similarly long-term untended space power plants. Because we outlined their design and performance characteristics previously, we discuss them no further here, but merely point to the high-pressure helium-cooled Brayton 'topping' cycle variant (without an associated Rankine 'bottoming' cycle) as the likely-preferred embodiment for space applications.

At the other extreme with respect to compactness and temperature of waste-heat rejection is the set of solar photovoltaic (PVA) options. If mass-economized to within several-fold of pertinent physics limits – i.e., to levels likely to be technologically accessible reasonably readily – thin-film photovoltaic materials surfacing loading-bearing and heat-sinking/-radiating sheet-assemblies suitable for in-space operation can be realized for of the order of 1 gram/m^2, and provide whole-spectrum conversion efficiencies of >10%. We consider it especially notable that thin-film solar PVA systems have enjoyed extensive penetration of the commercial marketplace for alternate electric power supply during the past several years at conversion efficiencies of >=10%, specific powers of the order of 1 W/gm, and prices not greatly in excess of $1/W. Indeed, the market for such PVA technology is currently of the order of 100 MW/year, and single production lines of 1 W/second sustained production-capacity are in operation, laying down amorphous silicon thin-films onto 14-inch-width stainless steel sheet of 7 micron thickness and lengths up to 7000 feet. Quite notably, early forms of this technology have been space-qualified as the primary power source on the Kvant module of the Mir space station.

Beam Conversion Systems And Entropy Rejection. When considering the type of beam to use for transporting power from space to Earth, one swiftly realizes that only electromagnetic radiation is suitable for beam-forming, and only small fractions of the electromagnetic spectrum at that; the requirement to penetrate the Earth's kilogram/cm^2 blanket of air precludes everything else.

The basic properties of beams of electromagnetic radiation are circumscribed by the Rayleigh criterion, which specifies that, if it's formed as carefully as ever possible, a beam comprised of photons of free-space wavelength λ and launched from an aperture of diameter D_1 can be mostly intercepted by a distant aperture of diameter D_2 if and only if the free-space propagation between the two apertures involves a distance not greater than L, where $D_1D_2 >= \lambda L$. This is a theorem of wave physics, not a technological rule-of-thumb; it can't be side-stepped or somehow 'worked around.' It's a remarkably simple statement of how well you can possibly do when forming and propagating a beam of any specified wavelength over any specified distance between 'sending' and 'receiving' apertures, e.g., transmitting and receiving antennae.

Since the cost of creating an aperture rises at least as rapidly as its area – i.e., rises as D^2 – one is strongly motivated to keep both D_1 and D_2 to as small values as may be feasible. [True, economics-of-scale might be argued to somehow make costs of large apertures rise somewhat more slowly than D^2 scaling, but 'optical figure'-maintaining stiffening requirements and the awkwardness of working at large scales can at least as readily be argued to make large aperture costs rise faster than D^2 scaling would indicate.] If the beam-propagating distance is more-or-less lower-bounded – as it assuredly is, in the space power-beaming context – then the only free parameter is the wavelength of the radiation to be beamed. For that reason, exploitation of the relatively few atmospheric transmission windows that exist is automatically directed to the shorter wavelength portion of the electromagnetic spectrum. These are the L-to-X-band microwave band, between ~2 and 15 cm wavelength, and the near-visible spectrum, between ~0.3 and 1.5 microns wavelength. These essentially define the technological possibilities within the physical constraints.

Glaser, in his historic proposals of a quarter-century ago, chose the microwave band, for well-understood reasons of (then, far-)greater technological maturity and thus more feasible economics-in-large-scales. His specific choice of 12 cm wavelength radiation adroitly side-stepped many regulatory issues, as this waveband is a largely unregulated one given to both industrial and residential uses (e.g., microwave ovens), and also accessed a very widely deployed – and thus very economical – technology-set. However, propagation of such radiation over distances of even 1000 km – about the minimum feasible to consider seriously for any wide-applications space power-beaming system – involves an aperture diameter product of ~10^9 cm^2, e.g., symmetric transmitting and receiving apertures each of 300 meters diameter(!). If the transmission-distance is greater – and Glaser's baseline system was proposed to be located in geosynchronous equatorial orbit (GEO), at 35 megameters altitude – then the aperture product grows proportionately; Glaser's proposed transmitting and receiving antennae were each several kilometers in diameter – and their estimated costs-to-implement (ignoring space-launch expenses, at that) were denominated in billions of dollars each. In order to not be completely unreasonable from an economic perspective, each of these apertures had to process time-averaged gigawatts of power, and thus had to be closely associated with either large terrestrial loads or high-capacity transmission lines; their very substantial real estate requirements generally precluded the former, so the various substantial (economic, environmental, time-delay,...) costs of the latter necessarily were placed 'in series' with those of the space power-beaming system itself.

Though economically burdened, Glaser's microwave-based proposal had the notable virtues of leveraging vigorously the COTS microwave-generating and –rectification technologies then already well-developed. The former could generate microwave power from the DC power available from solar PVAs (or space nuclear reactors, or whatever) with ~70% efficiency, and could reject waste heat at intermediate temperatures with acceptable (if not really excellent) radiator-mass efficiency; the klystron and magnetron designs were well-suited to exploitation of the abundant vacuum environment. The rectenna elements proposed for converting received microwave power at Earth's surface to DC (preparatory to exciting AC transmission lines) offered >50% efficiency, and could be cooled acceptably with ambient air. In-space power manipulation prior to microwave generation sourced several percent of low-temperature waste heat, but this could be radiated into space readily within the already-very-large mass-budgets of the ~10 km^2 transmitting antenna.

"That Was Then; This Is Now." In considering what may be the preferred form of space-based power-beaming systems for the early 21st century – essentially, in updating Glaser's proposals in the light of humanity's present technological posture and its associated economics – we must note that the constant-value-dollar cost of space-launch hasn't fallen nearly as rapidly as most everyone projected, a quarter-century ago. [This surely accounts in large part for the continuing failure-to-materialize of space-sourced power.] Indeed, were it not for the currently severely-depressed market for space-launch, the per-pound cost of putting mass into the 'standard' low Earth orbits is not sensibly lower now than it was back then. Thanks to the very recent advent of government-sponsored EELVs in the U.S., albeit without any really substantial market for the space-launch services thereby made available, space-launch to low-latitude LEO presently can be purchased at a per-pound cost of perhaps $2500, about half of what it was a half-decade ago, and likely not much more than half of what it'll cost at the end of the present decade (all in then-year dollars). [Contemporary space-launch costs to GEO remain 'stuck' at nearly 4 times that to low-latitude LEO; however, this may change drastically – and soon – as is discussed further below, and, in turn, may drastically impact the cost-efficiencies of almost all types of space power architectures.]

The impetus to reduce the 'buy-in' costs of space power systems strongly motivates reduction in the mass launched into space – wherever they may eventually end up being operated, for space-launch costs thoroughly dominate total system costs in all known and contemplated space power-beaming architectures of the present era. This basic economic consideration, in turn, not only impels use of the highest specific power technologies – those capable of processing the most (system efficiency-weighted) watts per gram of component or sub-system – but *also* the initial creation of the smallest, i.e., lowest-mass space power stations that make technical and economic sense. As is discussed further below, relatively small stations – ones sourcing megawatt- vs. gigawatt-scale (collections of) beams – may be eminently useful along an entirely different programmatic axis: 'wedging' into marginal markets at the commencement of the space power-beaming era.

For all of the above reasons – as well as other which will become apparent – we suspect that beamed space power will become most useful with lowest overall programmatic risk if the near-optical waveband is employed in lieu of the microwave one, under presently-prevailing circumstances. The corresponding 5 order-of-magnitude reduction in wavelength confers a intrinsic 10 order-of-magnitude reduction – a 10 billion-fold drop -- in the minimum area-product of the transmitting and receiving apertures of the product, a factor so huge that it permits entirely novel technical solutions to be exploited, as we'll discuss below. The totality of such exploitations, we believe, may make all the difference – e.g., between futures which continue to be devoid of space power and ones rich in it.

Beam-Forming And Projection Means. We propose to convert solar PVA power into optical-wavelength power in a manner tightly integrated into the PVA system itself, both in order to maximally economize on DC power transmission within the space power station and – at least as importantly – to reject waste heat with maximum efficiency. Specifically, we propose the use of laser diodes to convert DC power *in situ* from each tiny segment of the array into (largely) incoherent optical power with slope efficiencies of ~60%, and to use this optical power to pump in parallel a huge multiplicity of fiber-optic lasers, with marginal efficiencies of ~70%. The essence of this idea is to leverage the last two decades of advances in optical communications technologies to 'harvest' PVA power locally, converting it within a meter of where it was generated via sunlight-absorption into coherent optical power, employing millions of near-microscopic laser-diodes conducting in-line pumping of doped optical fibers, so that the lightwave intensities in the network of optical fibers grows continually as the very many individual fibers thread their respective individual ways from the extremes of the total power-station PVA into the station's central beam-forming locus. Quite usefully (as will be seen below), the coherent radiation thereby gathered into the station's beam-former is monochromatic. The power flowing into each laser diode would be on-off-switched by a control-line from the power-station's central computer; such a power-control system might be conveniently implemented with different-wavelength optical signals counterpropagating along the optical fiber which is being pumped by the controlled set of laser diodes.

The waste heat from the laser diode pumping – amounting to ~30% of the total electrical power of the PVA – must be radiated back into space, for there's no other place for it to go; moreover, it must be so rejected from the space power station at/about 300 K temperature, as these COTS diode-stacks have been intensively engineered by telecommunications technologists for near-room temperature operation. The corresponding radiator area required is less than a tenth of that of the PVA that sourced the power fed into the diodes, naturally suggesting that at least a fraction of the PVA itself be pressed into second-use as the 300 K thermal radiator. This in turn motivates the proposed use of highly-distributed, intimately-integrated tiny diode assemblies all over the PVA, so that the required room-temperature heat-transport – 'spreading' of the dissipated heat from diode junctions into adjacent thermally-radiating sheet – will involve as little dedicated mass as ever possible. It appears that such dedicated mass may be reduced to *de minimus* levels by implementing the PVA as thin-film photovoltaic material carried on a thin sandwich comprised of a pair of micron-thickness metal sheets patterned on their facing surfaces with an interposed lacework of microscopic dimensions partially loaded during manufacture with a suitable fluid, e.g., water, so as to function when pressed together in vacuum as a sheet heat-pipe (actually, a huge interlaced community of tiny, slender, mutually-vacuum-tight and thus functionally-independent "heat-pipettes", in order to assure long-term in-space operability); such sheeting then can function as a thermal superconductor up to several hundred Watt/cm^2 local thermal inputs, spreading room temperature-inputted heat over >10^3-fold larger areas for radiative rejection with degree-scale temperature-drops. Incident solar energy thus may be converted into DC power with 10-20% net efficiency (the remainder going directly into PVA heating and thus thermal radiation back into space). After this DC power is transported over short metallic lines heat-sunk directly into the PVA, it's expended in a local laser-diode that pumps an optical fiber-laser which is passing-through the area, and the waste heat is sunk back into the thin metallic sandwich-sheet comprising the structural support for the thin-film PVA material; the total distance-traveled by the DC+thermal power within the space power station thus is kept to <1 meter.

Optical fibers implemented in modern technology are famously low-loss power-conduction media; nonetheless, they must be more-or-less continually heat-sunk onto the PVA during their transits across the entire station to the beam-forming sites, as their tiny sizes makes them effectively incapable of shedding any useful power into thermal radiation. Very notably, the best of them are capable of continuously transporting exceptionally high optical intensities – hundreds of megawatts/cm^2 – so that modern single unimodal fibers of the order of a tenth the diameter of a human hair can transport a few dozen optical watts. Even with tapered-index jackets, the best modern fiber-optic *bundles* thus can transport in excess of 10 MW/cm^2; a 5 cm^2 set of bundles could carry the output of a 12% efficient PVA with 40% photodiode-to-fiber laser efficiency – 5% overall conversion efficiency – when the PVA was a kilometer in diameter.

The exceedingly high spectral brightness -- combined with the very large radiance (i.e., the intensity per unit of solid angle of uncorrectable beam divergence) – available from contemporary fiber-optic technology enables especially simple – and thus early-time feasible – beam-forming. For example, a set of fibers selected for serving a single Earth-based load may be coaxially-positioned behind a projection-lensette, which in turn illuminates with the (suitably mutually phase-scrambled and overall soft-apodized) outputs of the fiber-set that it subtends a distant, main projection aperture. This distant aperture – situated perhaps 1 km away from a large set of projection – would be shared by all of the projection lensettes of the station, since they could all be focused comparably well by one-and-the-same main beam-projecting aperture, their extraordinary spectral brightness considered.

We contemplate a main projection aperture comprised of a mass-optimized Fresnel phase-plate lens, likely implemented as a few-microns thickness of a suitable dielectric (e.g., a space-environment-compatible polyimide). Its diameter would be several times that indicated by the station's Rayleigh range to a minimum-diameter receiving aperture Earthside, so that it would be able to project suitably formed beams with so-called 'boxcar' intensity profiles onto distant receiving apertures, moreover even at significant off-zenith illumination geometries, i.e., so that there would be strictly-minimized 'spill-over' of the projected beam beyond the edges of the Earthside receiving antenna. For instance, a space power-station in GEO could project 1 micron-wavelength – i.e., near-infrared -- beams to Earthside receiving antennae of 1 meter diameter with a main projection aperture of ~40 meters diameter; however, we contemplate use of one for this application of 100-150 meters diameter, to more fully enable projection of 'tight' beams to Earthside receiving sites in all geometries. This main projector would have a f-number of the order of 30, or a focal length of roughly 3.5 km, so that it would magnify motions in its beam-forming region by a factor of 10^4, if it were situated in GEO and beam-projecting to LEO. Ground motion of a km would correspond to a 10 cm motion in the beam-forming region, and ground-speeds of 30 m/sec – roughly 60 MPH – would correspond to speeds of 3 mm/sec in the beam-forming region. The effective instantaneous field-of-regard of such an aperture would be ~4000 km from side-to-side, roughly the east-west distance across the United States. In other words, this main projection aperture could project optimally-focused power beams within a meter-diameter aperture anywhere across a disc on Earth which would cover the continental U.S., moreover without moving the aperture at all; all that would be required to move would be the sub-mm-scale optical fiber-lensette sets in the 0.3 km-wide beam-forming region.

Beam-Reception And Electricity Generation. Earthside power-beam reception may take place on a wide variety of scales and locations, across a rich spectrum of higher-value applications for electricity (and perhaps for low-temperature waste-heat, as well). Since we expect that initial stages of market penetration will be with relatively high-cost power-beam – or, at least, for power that is desired to be sold at comparatively high unit prices – we emphasize the providing of beam-power under circumstances of greatest-possible-convenience to the set of highest-value applications. We anticipate leveraging the intrinsic spatial and temporal agility of space-sourced power beams to put down beamed energy *quite* exactly where and when that it's desired (and, of course, paid for) – and nowhere else. Presently available high-precision geolocating GPS receivers suitable for the mass market and recently-arrived real-time, high-bandwidth, low-cost global telecommunications connectivity via the Global Digital Network – along with global financial transaction-executing and account-clearing services -- are seen as necessary-&-sufficient to enable beam-agile servicing of virtually the full spectrum of markets for on-the-spot-delivered electrical power and energy: ***you get delivered just what beamed energy you contracted for, exactly where-&-when (to within the nearest few dozen centimeters and the nearest dozen nanoseconds) you specified to have it delivered, at the time-programmed rate(s) that you specified for its delivery, with at most a quarter-second time-delay between contract-execution and commencement of energy delivery.*** Such heaven-sourced Promethean fire, we suggest, will indeed "prove the means to mighty ends."*

We anticipate conversion of beamed power so received into electricity with photovoltaic converter array-material specifically designed for maximally-efficient conversion of the particular spectral characteristics of the beamed radiation, i.e., a reasonably wavelength-optimized converter, for which efficiencies of 50-70% have been demonstrated in square-meter-scale modules. [High conversion efficiency is of dual significance: first, it maximizes the desired product – electrical power – and, second, it minimizes the waste heat generated in the array which must be offloaded into ambient air, water, etc.

Premium customers presumably will demand that their beam-generated electricity be sourced from as inexpensive, compact, lightweight and low-volume package as is possibly consistent with reliable, safe operation. We therefore anticipate that the exceptionally high-brightness nature of the beamed radiation will often be exploited to deliver beamed power at substantial multiples of that available from Sol-beamed power – ordinary sunlight. We expect that many premium applications will desire to have 1-10 kW of electricity sourced from a ~1 meter^2 beamed-power-receiver assembly, i.e., one with the scale – and perhaps the mass and even the portability – of a large umbrella. [Indeed, it's our present estimate that this may even characterize the "sweet spot" of the eventual mass-market for beamed power.]

Serving such markets will involve beam-intensities of 10-100 times that of sunlight, so that such beams – particularly the ones at the more intense end of the range – will pose safety risks. Our basic response to all such issues is a combination of passive physical barriers – e.g., tight-mesh fences, so that human body-parts, e.g., fingers, can't be inserted into beams without intensive, deliberate effort – and automatic safety devices, such as beam-interruption detectors completely around the perimeter of all receiving apertures which command immediate beam-shutoff when any single such detector senses even momentarily diminution of local beam intensity. Given the fifth-second loop-closure time for even the most distant space power-stations of present interest – those in GEO – this suffices to ensure that any beam-induced burns will be at worst second-degree ones, even for 100X-sunlight power-beams. [We note that such systems can be implemented with any desired degree of redundancy and with 'perimeter defenses' of any desired degree of stand-off distance-&-time, so that risk of any politically-specified extent-of-damage may be made as statistically unlikely as may be politically determined – and all this can be accomplished with small-to-negligible economic costs. Moreover, automatic, asymptotically-zero-cost, millisecond-by-millisecond record-keeping at multiple points – the ground antenna, the ground control system, the space power station, etc. -- can readily assign the physical bases of liability essentially as precisely in spacetime and as incontestably as may be politically specified. Automatic beam-shutoff, followed by automatic low-intensity receiver-occlusion-checking, followed by automatic-&-conditional full-beampower-restoration, should aptly address even the bird-loss issue-set, over-&-above the inadvertent airplane one.]

<u>Control And Concept-Of-Operations</u>. A sketch of a few of the basic concepts-of-operation may serve to illustrate how we believe a space-origined power-beaming system might serve the upper-end civilian marketplace for electricity. We sort this by class-of-customers, aligned along the epoch-of-first-use axis.

<u>First Customers</u>. The earliest customer-class for power beamed from space is likely to be found fairly exclusively in out-of-the-way places, generally far away from utility lines – though occasionally merely unable to access ones near-at-hand (e.g., in a sailboat-in-harbor but not at-pierside); in his/her then-prevailing circumstances, (s)he is quite insensitive to the cost of electrical energy or power; 1-100 megajoules of electrical energy have a perceived worth no less than dollar per megajoule. [E.g., a 'dead' car battery can be induced to crank most engines successfully with an infusion of ~0.1 megajoules of quick-charge energy.] An example of such a customer might be an economic upper-middle-class guy who likes the conveniences of electricity but hates lugging around massive batteries and/or a motor-generator set. Instead, in his backpack – he may be a civilian, or a soldier-with-USG-credit-card – he carries an umbrella-like object, which he unfurls at a location-&-time of his choice and plants onto the local terrain. He then makes a call on his PDA-phone and contracts for power to be beamed at a specified intensity-vs.-time onto the geolocation specified by the GPS receiver positioned at antenna-center of his umbrella-esque power-unit, accepts the liability-waiver and executes the funds-transfer as cued by his communicator unit. A power-up cycle is then automatically executed; if the low-power beam initially transmitted reaches all portions of the antenna in the *a priori* predicted manner, full-power-beaming is commenced, and is then maintained for just as long as the non-occluded condition-set continues to exist; otherwise, the customer is cued to correct the beam-interruption condition. Electrical power flows from the receptacle on the antenna-handle into his local load, for as long as he may have contracted, upon to whatever maximum rate-vs.-time may have been contract-specified. He's executed a take-or-pay contract; when he's got all the power that he needs, e.g., to recharge a battery-set, to cook a meal, or whatever – he simply folds up his antenna and moves on; the power-beam evaporates essentially instantly, even if he didn't tell it to do so. [If he formally canceled the remainder of his service via his communicator, he might get some credit to his account for the unused power/time, e.g., if the then-existing 'spot market' for beamed power in his general sector of spacetime permitted the beam scheduled for him to be re-sold to another 'spacetime-adjacent' customer.] At any given time, there may be 'only' thousands of such customers per million square kilometers – but we anticipated that space-beamed power service will start with space power stations having beaming capabilities of mere megawatts, so this potential customer-base would saturate

capabilities, i.e., will *bid*-&-pay 'top dollar' for the power that's initially available – thereby maximizing both ROI and incentives to swiftly expand the total beaming capacity.

Early Adopters. Leading-edge technologists in the contemporary West are blessed with a class of techno-masochists known as "early adopters," people who will pay-&-suffer for the privilege of living-&-working on what's colloquially know as "the (b)leading edge" of modern technology. Though generally not individually wealthy, this sub-population in aggregate commands very substantial economic resources, which are reliably thrown at any advanced, new, technically-challenging, politically-ultra-correct, or somehow enjoying the repute of being 'cool.' [For example, although the authors fancy themselves as more-or-less-normal folks who have similar-type friends, they know of two colleagues who *elected* to create – out of salary-based income – solar-electric homes, ones energized entirely by solar photovoltaic power.] These folks will commence to buy space-beamed power as soon as it becomes available for of the order of $1/kWh, for 'special purposes.' Among these will be recharging of batteries on their electric cars while parked, so as to enable such range-'marginal' modes of personal transportation to be used reliably for longer-range journeys. Since this involves beamed power of specified total time-integrated magnitude but indifferent as to time- or (within wide limits) rate-of-delivery to the receiver, such 'salvage' loads will initially be serviced with power which would otherwise go unused, e.g., which is 'abandoned' unexpectedly by take-or-pay customers; they'll thereby be enabled to enter the beamed-power market relatively early – to limited extents. These customers will simply purchase energy delivered within a specified time-interval to a specified site, with specified minimum and maximum rates – likely with specified not-to-exceed prices for each of two or three blocks of energy-delivered. [For instance, a customer might be willing to run the hydrocarbon-powered engine in the car, in spite of the very high price of its fuel, in order to get to work or to return home, if the price of energy somehow was exceptionally high that day, but would buy beamed energy in various quantities over the next several hours, "if the market-[price is right." This customer might place a beamed-energy delivery order accordingly, just before leaving the parked vehicle – or might contract for delivery of energy at a roughly-fixed location, within a specified time-window, days in advance, in order to secure lower take-or-pay pricing for the desired energy-block(s).]

Mobile Customers. Roughly contemporaneous in market-penetration epoch with fixed-site 'early adopters,' we expect, will be the first mobile customers. The large majority of these will be commercial and personal vehicular transportation-users, buying power beamed to the rooftops of their vehicles. Depending on vehicle scales – two-seaters to large commercial truck-tractors -- and the speeds at which they're driven (e.g., urban stop-&-go to high-speed hill-climbing on interstate highways) – such vehicular loads will vary between 3 and 100 kWe, and will involve receiving antenna-areas of ~0.5-10 square meters. These mobile customers will be 'inspired' to buy beamed power by high local fuel costs – be they market- or tax-driven – when the price of beamed energy descends through thresholds. For example, in Europe at the present time, the fully-taxed cost of motor vehicle fuel is equivalent to a cost of electrical energy-delivered-to-the-vehicle-at-time-of-use of about $0.60/kWe; if the differential costs of heat-engine and electrical power-trains and of maintenance thereof are included, this 'energy-source indifferent' cost-level rises to $1.00-1.25/kWe-delivered-at-use-time, depending on car size and driving modes. Thus, if electricity could be delivered to such vehicle-customers at, say, $0.7/kWe, when-&-as they need it, a Eurocentric energy market of titanic size for energy/power beamed from space presumably would open as quickly as automotive power-train retrofits can be performed, driven by pure-&-simple cost-avoidance behaviors.

Due almost exclusively to lower taxes, the 'energy-source indifference' cost of timely-delivered electrical energy in America is lower by about two-fold: to ~$0.30/kWh if only energy costs are considered, or ~$0.5/kWh, if all costs-avoided are considered. The notably differing cost-levels between and within these two huge energy markets naturally provides a very attractive growth-plan for space-sourced beamed-power to mobile customers of all types.

Servicing mobile customers may be considerably easier from technical vantage-points than it might first appear. Most such customers may have either limited on-board energy-storage capacity – e.g., a rechargeable, secondary-type battery – or an on-board prime-mover of limited power – e.g., a hydrocarbon-fueled engine-generator pack sufficient to operate the vehicle at reduced speed (and with a modest fuel-tank capacity good only for quite limited unrefueled range). Such customers may enter into a more-or-less dynamic power-purchasing contract, one 'steered' both by ongoing power-demand from the vehicle's as-commanded power-train and by the GPS-determined time-varying position of the vehicle – and presumably bid price-clamped at some predetermined-to-be-acceptable unit cost of delivered beam-energy. The vehicle operator's on-line 'agent' – the car's motive energy-bot -- would then bid from time-to-time for beamed energy delivery, while simultaneously looking at the state of battery-charge, the differential cost of battery-energy (appropriately discounted for considerations such as depth-of-discharge shortening of battery life of known capital cost-to-replace), the remaining duration (in energy) of the present day's trip, pending beam-obscuration by long tunnels and bad weather, driver reluctance to proceed at reduced speed over significant travel-distances with vehicle engine-generated power, economic costs of engine-generated energy, etc.

Technically, it's quite readily feasible to keep power-beams centered on vehicle-tops, even as they maneuver in traffic, make emergency stops, etc., as brief consideration of Newton's Second Law makes clear: vehicles are typically equipped with 3-5 times the brake horsepower as they have motive horsepower, and can slow-while-breaking at a maximum of 0.3-0.5 gee. The loop-closing time from the vehicle beam receiver-centered GPS antenna to the power station-in-GEO and back-via-powerbeam is 0.2 seconds, during which time a sustained, unanticipated vehicle acceleration of 0.5 gee (the all-parameters worst-case) – 5 m/sec^2 – has induced a power beam-center-offset of 0.25 m, much smaller than the meter-diameter-scale beamspot itself; the vehicle's sending of not only its GPS-computed velocity but also of its time-varying acceleration would quickly – in ~0.5 second – reduce the beam-aiming error to <0.1 meter for the remainder of the emergency-braking episode. As already noted, maximum-available-acceleration from the vehicle's powertrain could induce worst-case beamspot-center offsets only 3-to-5-fold smaller than the emergency-braking ones. The 'bottom line' is that the completely non-intuitively-large value of lightspeed and the relative nearness of GEO, together with the geolocation and signaling capabilities of early 21st century technologies, combined to permit cooperative Earthside motor-vehicles to be beam-spotted from GEO with remarkably high precision, even when they're accelerating at their respective 'physics limits.'

<u>*Mass Market Customers*</u>. The present price of energy delivery to stationary-type mass-markets in the U.S. is $0.06-0.3/kWh during peak-use hours, this range covering preferred residences (and some farms) and non-preferred commercial customers. These prices are widely understood to not be market-determined ones, but rather are politically prescribed. If-&-when market-rationalized, time-of-use pricing of electricity becomes at all widespread, peak-use energy will sell to end-use American customers for at least $0.25 to $0.50/kWh – just as it routinely has done at wholesale, over the past several years. Servicing peak electrical system loads – necessarily, of *a priori* unknown magnitudes – is just amazing costly, and relatively economically liberal American wholesale electric markets reflect this basic reality, even if the politically-constrained retail ones currently do not.

Such rational pricing of peaking power will bring it into the range at which the American motor-vehicle 'load' has already enticed ever-more-economical space-origined power-beamed electricity. The stationary-load mass-market will then be accessed, likely driven by canny individual customers in homes and businesses conducting local, computer-driven arbitrage against the local utility against the background of their internal needs and their rooftop power-receiving capacities. As the time-dependent price of space-origined power drops – and the GEO power-stations become ever more adept at following the solar-phased electricity demand-peak as it sweeps diurnally around the Earth – such arbitraging will enable ever-deeper penetration by space-beamed power of the mass-market for electricity, until ground-based electricity-supply systems become very high economic efficiency, base-loaded ones. At that, such currently-conventional systems will always be disadvantaged by the full set of transmission and distribution costs – economic and otherwise -- stacked on top of their 'bus-bar', or generation, costs; these transmission and distribution costs are entirely avoided by beamed-to-the-load-upon-demand technology.

'Free' Technologies And Tech-Demonstrations. We believe that the many advantages – both quantitative and qualitative -- offered by space-sourced power-beaming are even now becoming apparent to key U.S. Government decision-makers, and that serious programmatic enterprises will commence reasonably soon to beam power through space in usefully large quantities and rates, following the basic path already blazed by space-beamed high-bandwidth information flows. Unsurprisingly, such moves are likely to be taken first by those responsible for national security. Such efforts are likely to be unusually purposeful, fast-paced and correspondingly well-resourced, relative to most large-scale National endeavors. It's reasonable to expect that the basic technologies found to enable these enterprises will be made available for other Government purposes soon thereafter; depending on top-level policy determinations, key technologies may be made available reasonably soon for civilian exploitation; the Internet evolving rapidly from the ARPANET base is the salient, potentially-pertinent example of such a dual-*used* technology-set.

Large-Scale Solar Photovoltaic Power Supplies. Interestingly high-capacity solar PVAs may be the first of the enabling technologies for large-scale civilian-applications power-beaming to be performance-demonstrated by the U.S. Government. While high-capacity electric power supplies have many potential national security-related uses, the single one which presently seems sufficiently compelling to justify sustained, serious effort in-&-by itself is the 'space tug' one overviewed below.

Space-Based Power Beaming. However compelling greatly-enhanced orbit-to-orbit space transportation may be, the beaming of power across space to other space platforms and from space to use-points on/near the Earth's surface may be of greater long-term significance. Transportation from LEO to higher Earth orbits currently imposes costs of known-&-large magnitude, thus making the 'space tug' technology-set of urgent interest; however, the ability to place beamed power where-&-when you want it, in whatever quantities and for whatever duration you need it, may be of far greater long-term importance. Therefore, the attention – and programmatic emphasis – given to realization of power-beaming from space by thoughtful decision-makers may not be less than that bestowed on creation and initial use of megawatt-class solar PVA power supplies.

'Space Tugs' And 'Orbital Homogenization'. The past half-dozen years have seen the advent of high-power, high-efficiency plasma-jet engines developing specific impulses of several *thousand* seconds. These can be used to transport payloads through large delta-vee changes with very modest costs in reaction mass, so that patience denominated in mere weeks can see power-intensive payloads – e.g., space power stations launched into LEO and deployed/assembled there – transported into essentially any other orbit, anywhere in the Earth-Moon system(!). The fraction of payload mass required to transit from GEO to LEO is currently ~10%, and near-term advances in engine specific impulse bid to reduce this to ~5%. The bottom-line consequence is that all orbits in cislunar space are comparably accessible in energy- (and thus in dollar-) cost. If mere weeks of transit-time delay can be accepted – and if large solar PVAs are available – then all points and all orbits in cislunar space becomes homogeneous in terms of access. [An additional feature of such 'space tugs' is that, as their name suggests, they're re-usable; once a payload has been hauled into a desired orbit, the engine-fuel tank-PVA 'tug' can detach and swiftly 'fly' to another use-point, there to commence transporting another payload to another destination.]

Lunar Materials Exploitation. Every undergraduate student of orbital mechanics understands that every orbit in cislunar space is 'energetically cheaper' to access from the surface of the Moon than it is from the Earth's surface – and that most orbits (including GEO) are 'cheaper' by an order-of-magnitude. Thus, if abundant lunar materials – notably structural metals such as Mg, Al, Ti and Fe, as well as photovoltaic ones such as Si – could be sourced to space manufacturing points in high orbits, the unit cost of systems in such space locations could be expected to undergo comparable, i.e., order-of-magnitude cost-decreases. A rational U.S. program to enhance the national posture as a spacefaring nation thus will necessarily include a lunar materials exploitation component, and civilian space power efforts can be expected to benefit correspondingly.

'Real World'-alities. T

Economics. It's surpassingly difficult to overemphasize the significance of economics when considering space-origined beamed power. Only if servicing an intrinsically cost-insensitive customer can such considerations be ignored – but perilously so, as such customers are also notoriously fickle, and their custom subject to all manner of interference, telling fractions of which are either invisible or unpredictable. Scrupulously respecting the economic realities is a *sine qua non* for all attempts to address markets in the real world – the really large-scale ones. Adapting to non-market practices is a time-tested recipe for creating a 'bonsai enterprise': it may be quite pretty from some perspectives, but it'll assuredly always be small.

Competition. As already noted above, no seller really likes to have competition appear in his/her markets. It's therefore preferable, to the greatest extent feasible, to have space-sourced beamed power initially serve markets that are not merely under-served, but totally non-serviced, by existing suppliers. There are many economically well-positioned customers who may surprise both the energy punditry and themselves by eagerly congregating to constitute such markets for spacetime-agile, on-demand beamed power from space, just as there were many people who surprised most everyone other than Craig McCaw by swiftly becoming the mass-market for mobile phone service, barely a dozen years ago. Everyone – notably including wireline telephone companies who happily sold call-completing services – benefited from the resulting intensified demand for telephony services.

Regulation. As we noted above, the best that can be hoped for with respect to governmental regulation of space-origined beamed power is rationality and competition-neutrality. These ideals are seldom, if ever, attained in the real world. Intelligent students of government regulation practices who are involved in space power-beaming enterprises will act accordingly. To be sure, there's genuine ground-for-hope, as the history-to-date of the Internet attests: if a technology is sufficiently novel and also sufficiently promising, all components of the bureaucracy have real difficulties in "getting their arms around it," and the more perceptive political leaders will actively harry-&-delay these stultification processes.

Conclusions. The prospect of space-originated power purposefully beamed to Earthside receivers for civil purposes will remain utterly becalmed into the foreseeable future – for the same basic reasons that bring us to the present juncture from Glaser's epochal proposals of a quarter-century ago – unless fundamental changes are made. In the foregoing, we've tried to sketch what appear to be changes both necessary and sufficient for power beamed from space sources to become of fundamental and lasting significance in human affairs during our lifetimes.

In spite of overt governmental participation in the economic affairs of humankind to the tune of 40-60% of GDP in the advanced economies, public bureaucracies in liberal democracies only very rarely undertake bold initiatives – ones involving major changes in the established orders of doing things – including sourcing the energy to run civilizations, for fundamental reasons that are very well-understood. Thus, if power beamed from space is to become widely available and extensively used, we believe that it'll be via basically private initiatives, and thus will meet the fundamental criteria and prerequisites of all such initiatives, including comparatively modest initial scales and relatively high risk-discounted rates-of-return on investment.

Such considerations suggest that space-based power-beaming involving relatively modest demands from customers who are willing to pay handsomely for electrical power-on-demand – i.e., anywhere and anytime, at any rate and for any duration – will comprise the crucial initial market for beamed power, the base from which expansion will inevitably and inexorably occur, perhaps even at extraordinary speed, post-breakout. We have sketched some of the technological means by which near-term capabilities to service such quintessential 'spot' markets might be realized, attempting to demonstrate that such systems may be realized for total initial investment within the private sector's scope.

We suggest that the extant technological base is sufficiently mature that such efforts could commence market-servicing by 2010, if serious, well-focused efforts were to commence today. If intelligently conducted thereafter, servicing of mass markets – involving dozens of GW of delivered electrical power – could be underway by 2025, and a large fraction of the total human demand for electrical energy could be space-sourced by 2050.

The environment consequences of such a fundamental shift in energy sourcing could be large, especially if electricity were to increase its share of total energy supply, e.g., by deeply penetrating the mobile energy-use marketplaces, as we've suggested may be feasible.